ENGINEERING CASE LIBRARY

ECL 68

Tape Recorder Capstan Shaft
at
Ampex Corporation

During 1960 and 1961 George Rehklau, a Project Engineer for Ampex Corporation in Redwood City, California, was working on the development of the mechanical components for a new portable professional tape recorder, the PR-10. This recorder is described in Exhibit 1. In 1966 models of the PR-10 series sold from about $1,000 to $1,400.

George said, "When we designed the PR-10 we wanted to improve the flutter characteristics and also the reliability and general mechanical quality. But we were also interested right from the beginning in low cost -- this is much more important in professional audio equipment than in instrumentation recorders which may sell for ten or fifteen thousand dollars."

Prepared in the Design Division, Department of Mechanical Engineering, Stanford University, by John A. Alic under the direction of Karl H. Vesper with financial support from the National Science Foundation.

Flutter is the measure of longitudinal variation in speed of the tape over the heads. George explained that it was measured by recording a 3 Kc tone on the tape and playing it back through an FM frequency discriminator -- or flutter meter. He said, "We then send the signal through a sound and vibration analyzer and a graphic level recorder. This gives a spectrum -- or spectro-analysis -- of the flutter, from a half cycle to 250 cycles. Knowing the frequency, we can pinpoint the source of the flutter -- for instance, capstan runout or even the grinding pattern on the capstan. To improve the flutter characteristics of the PR-10 we attacked both capstan and the tape reel hold-backs."

The capstan meters and drives the tape, as shown in the sketch of Exhibit 2. It is a small diameter motor-driven steel shaft against which the tape is held by a rubber idler wheel; in Exhibit 1 the capstan and idler are visible on the front of the machine between the head cover and the empty tape reel. George explained that the capstans on all recorders have small O.D.'s so that the capstan speed can be high. Flywheels are used on the capstan shaft to damp out speed fluctuations. High speeds allow flywheels of a reasonable size. The lower limit on practical capstan diameter is set by wear and by manufacturing costs. Tolerances on the shaft must be very tight to minimize flutter. Allowable runout on the PR-10 shaft is .0001 inch T.I.R. in 6 inches. If the shaft diameter is too small, it will warp and bend easily. The diameter of the PR-10 shaft is .3123 - .3125 inch.

Various PR-10 models offer speeds ranging from 1-7/8 ips (inches per second) to 15 ips with the .3125 inch capstan. The similar CL-10 has a capstan of half this diameter for speeds down to 15/16 ips but the rest of the shaft is the same size as on the PR-10. The drive from motor to capstan shaft is by a flat rubber belt running over stepped pulleys which provide the different speeds. Although the capstan actually controls the tape speed, the motor is also connected to each reel through an eddy current clutch (the "hold-backs"), the feed reel being braked and the tape-up reel driven, to keep the tape in tension. The object again is to minimize flutter. The torque on the reels is constant, with the result that tape tension varies from about 2 to 6 ounces depending on the amount of tape on each reel.

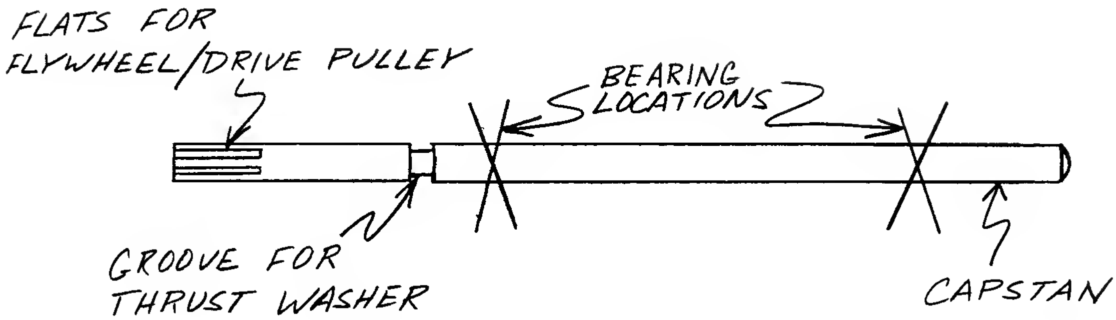
George said, "This change in tension results in a speed error of .15% from the beginning to the end of a reel, caused by slippage of the tape at the capstan and of the drive belt. This is well within the spec of $\pm$ .25%, however."

The rubber idler wheel is pressed against the capstan with a force of about five pounds by a solenoid. Drive belt tension, which acts in the same direction as the idler load, is about eight ounces. A two pound flywheel on the end of the capstan shaft also serves as the belt pulley. The tape is 1/4 inch wide and .0019 inch thick, the mylar or acetate backing being .0015 inch thick and the remainder an oxide coating on one side. On the PR-10 the angle of wrap of the tape about the capstan is 15°; George explained that the coefficient of friction of the tape on the capstan depends on the tape, but is generally around 0.2.

George said, "Although matched duplex ball bearings, which are machined and ground in pairs, are used on the capstan shafts of some high priced recorders, they cost $40 to $50 a pair and are much too expensive for the PR-10. Other types of ball bearings allow more runout than we wanted -- even Class 7 bearings have a runout of one and a half tenths. We could have tried an oilite bushing or a grooved and graphited bronze bushing, but both of these rely on boundary layer lubrication and we knew from past experience that this would break down intermittently, giving a tendency towards jerking and irregularities. We had never used a sleeve bearing with a sustaining oil film before, but we decided on this course for the PR-10. This tied in with our low cost objective in two ways, first because the bearing would be inexpensive and also because we wanted to use a stepless shaft and sleeve bearings are well suited to this. Capstan shafts must be ground to control dimensions and surface finish. We wanted to design a shaft without any changes in diameter so we could use centerless grinding, which is much less expensive than grinding on centers."

George continued, "We had the basic layout for the machine by this time and knew we wanted the centers of the two bearings about 2 3/4 inches apart on a 6 1/2 inch shaft. We planned to use a split thrust washer in a groove just below the bottom bearing."

The proposed shaft is sketched below:



The thrust washer is slit along a diameter so that it can be fitted into the groove. George planned to use two bronze sleeve bearings with their O.D.'s machined spherical so they would be self-aligning. On either side of each bearing would be a felt washer to serve as an oil reservoir. The oil was to be a turbine spindle oil, Mobiloil DTE light, with a viscosity of 150 seconds at 100°F. This oil is used in all Ampex machines because of its high resistance to oxidation. This is a critical property, since the machines may have to function over a period of years without service.

Next George had to design the bearings themselves, determining a set of parameters which would provide a sustaining oil film at the extremes of shaft speed.

Conclusion

George Rehklau designed the bearings for the capstan shaft using a set of charts which had been published by Machine Design magazine. However, his calculations showed that at the slow 1 7/8 ips tape speed, it would be impossible to develop an oil film. George then thought of cutting a spiral groove into the shaft to pump oil into the bearing. He said, "We don't know exactly what this does, but the idea was to put the oil under pressure to get a load bearing film. This is evidently what happens, because we could see the oil bubbling up out of the top on the bearing in test rigs. I had seen spiral grooves before in motor shafts; GE fan motors use them and run for tens of thousands of hours without attention."

A drawing of the capstan shaft appears in Exhibit 3. The bearings and felt washers are fitted into a die cast aluminum housing as shown in Exhibit 4, where items 10 and 11 are the felt washers and items 5 are the bearings. Item 13 is the split thrust washer. A bearing is shown in Exhibit 5. The longitudinal hole allows oil to return from the upper felt washer to the lower washer after it has been pumped through the bearing by the spiral groove.

The centerless ground shaft for the PR-10 costs Ampex $1.80 to make, as compared with a cost of $15 to $18 for stepped shafts ground on centers which are used on other recorders. The groove, which is cut on a lathe, is continued along the length of the shaft between the two bearings because this is the easiest way to make it. George explained that tolerances on the parts of the capstan assembly were determined by putting machines together with different combinations of dimensions and surface finishes and measuring flutter. From the spectro-analysis satisfactory tolerances for each part were obtained.

George commented, "The size of the spiral groove was determined by cut and try, but this was the only thing we changed in the capstan assembly during development. When we finished the development work, the Quality Audit group ran life tests on five prototype machines, an average of about 3,500 hours each. They ran one minute cycles of play, stop, rewind, fast forward,

rewind, stop, and so on. The sleeve bearings worked fine, and the shafts showed no wear after hundreds of hours."

The design and development of the PR-10 took 18 months from the first layout to the release of the drawings, of which the last three were spent working almost entirely on the drawings. Several additional prototype machines were built during this period as an aid in checking the drawings.

Questions

1. How do you suppose the spiral groove actually affects the performance of the sleeve bearing?
2. Perform an analysis and calculate the expected slippage of the tape as it passes over the capstan. Concerning this problem George said, "As far as I know this has never been figured out, but it's something we'd certainly like to know."

AMPEX Exhibit 1

PR-10 SERIES

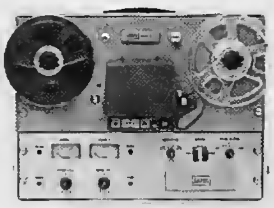
COMPACT STUDIO QUALITY RECORDERS

An advanced concept in recorder design, the PR-10 series provides Ampex Professional Recording Standards in a new, compact instrument. These recorders assure studio quality and performance for all field and studio applications . . . for broadcasters . . . recording studios . . . educators . . . churches . . . industry . . . and advanced recordists. Major new engineering advances permit COMPACT SIZE WHILE RETAINING FEATURES AND PERFORMANCE OF STUDIO CONSOLES.

PR-10 FEATURES . . .

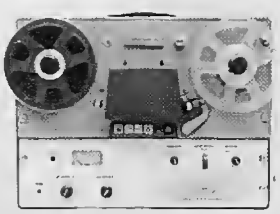
- MODULAR DESIGN ALLOWS PORTABLE OR RACK MOUNTING
- ONLY 14 INCHES OF RACK SPACE REQUIREO
- COMPACT ELECTRONICS WITH FRONT PANEL AOJUSTMENTS
- PUSHBUTTON RELAY/SOLENOID CONTROLS
- COMPLETE REMOTE CONTROL OF ALL FUNCTIONS
- PLUG-IN EQUALIZERS ANO TRANSFORMERS
- HYSTERESIS SYNCHRONOUS ORIVE MOTOR
- AOVANCEO 4-POSITION HEAO ASSEMBLY
- 4-TRACK PLAYBACK (WITH OPTIONAL HEAD)

PR-10 MODELS . . .



STEREOPHONIC MODEL PR-10-2

The versatile PR-10-2 provides 1) complete stereophonic record and reproduce, 2) monophonic record and reproduce with many of the new two-channel techniques now being used, 3) conventional monophonic use (½ track). Separate-track erase head in combination with "record/safe" selector permits half-track recording of either track, sound on sound, cue tracks, and other special effects. Fourth head position can be used for quarter track playback head.



MONOPHONIC MODEL PR-10-1

The PR-10-1 is a one channel recorder available with full or half-track heads. Transports are the same as the PR-10-2. Single-channel electronics have the same professional design and construction as the two-channel version, but with a built-in mixer that can mix line and microphone or two microphones (by using a plug-in mike preamp in the line input). The PR-10-1 can be used with AME or CCIR plug-in equalizers.

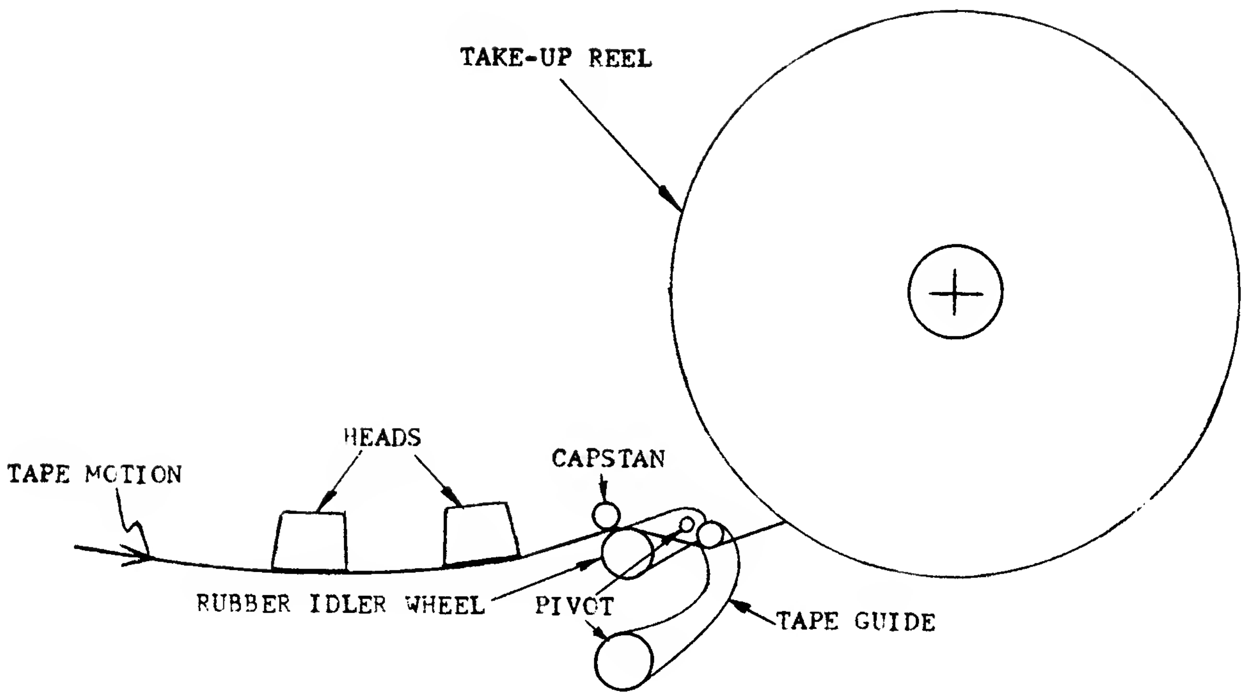
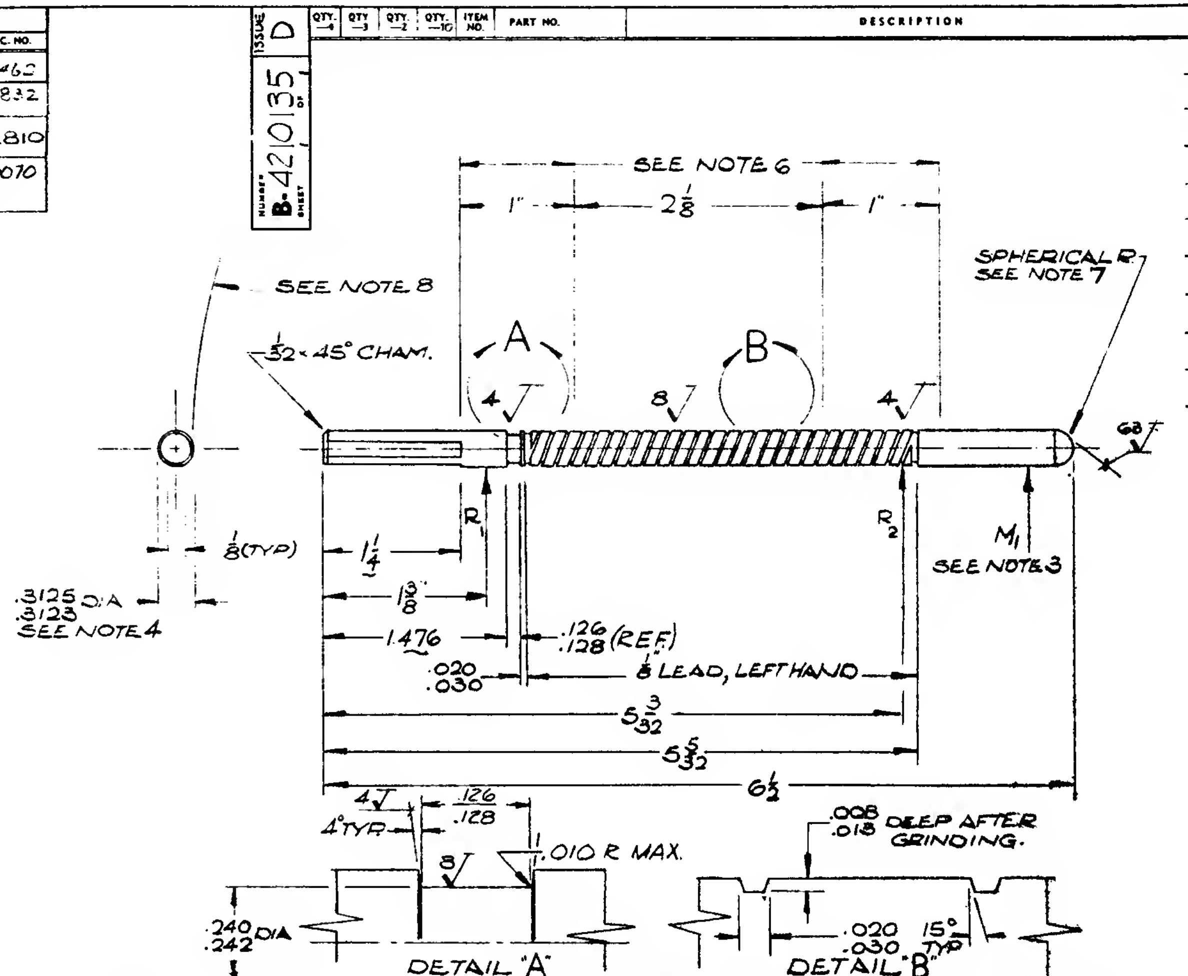


Exhibit 2: Schematic Drawing Showing Capstan and Idler Wheel.

REVISIONS						
ISSUE	DESCRIPTION	BY	CHKD.	AUTH.	DATE	E.C. NO.
A	RELEASED FOR PRODUCTION	[illegible]	[illegible]	[illegible]	[illegible]	10462
B	ADDED NOTE 9	[illegible]	[illegible]	[illegible]	[illegible]	10832
C	DWG.NO.WAS 21-0135-01	[illegible]	✓	[illegible]	[illegible]	12810
D	ADDED .126/.128 DIM TO DETAIL A-DWG CLARIFICATION	RJC	[illegible]	[illegible]	[illegible]	50070



NOTES--

1. Heat Treat and Stress Relieve To 55 Rockwell "C" Minimum.
2. Centerless Grind and Polish To Surface Finish Shown.
3. With Shaft Supported As Shown At "R_1" and "R_2" Indicator Reading Made at "M_1" To Be Within .0001 T.I.R.
4. $\frac{.3125}{.3123}$ Dia. Must Have Less Than .00005 Surface Irregularities Due To Grinding Pattern.
5. Demagnetize After Machining.
6. Indicated Areas To Have A Finish Of 4√
7. Spherical Radius To Be Concentric With Shaft Within .005 T.I.R. After Heat Treat Remove Oxide From Spherical Rad.
8. Radius Optional 2 Places, 6" Min.
9. **No lateral scratches permitted on surface of part.**

DASH NO.	MAT'L. SPEC.	STOCK SIZE	MATERIAL
-10	DA1-10	—	STL. COR RES. 440C OR 440F

ALL DIMENSIONS ARE AFTER PLATING

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

BREAK SHARP CORNERS .005 R. MAX.

TOLERANCE ON DECIMALS ±.005 FRACTIONS ±1/64 ANGLES ½°

SAMPLES MUST BE SUBMITTED AND APPROVED BEFORE PROCEEDING WITH PRODUCTION

SCALE: 1/1

DO NOT SCALE DRAWING

		DATE
DRAWN BY:	J. Blacke	6/6/61
CHECKED:	[illegible]	7/6/61
PROJ. ENG.:	[illegible]	7/6/61
APPROVED:	[illegible]	7/6/61

TITLE: SHAFT - CAPSTAN

AMPEX AUDIO INC. SUNNYVALE, CALIFORNIA

USED ON: MODEL PR-10, NEXT ASSY. 4030186

NUMBER: B-4210135

SHEET 1 of 1

Exhibit 3: Capstan Shaft.

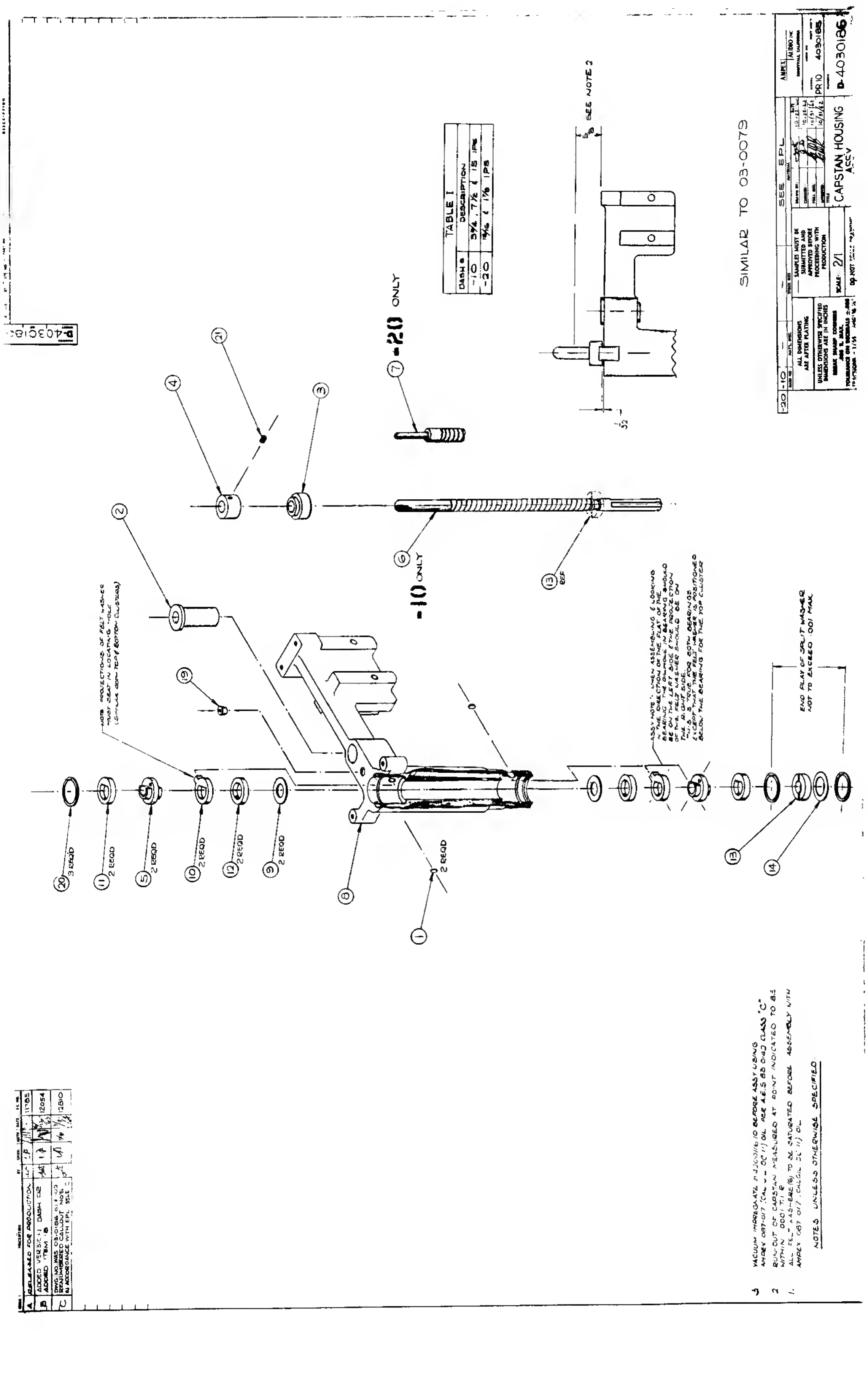


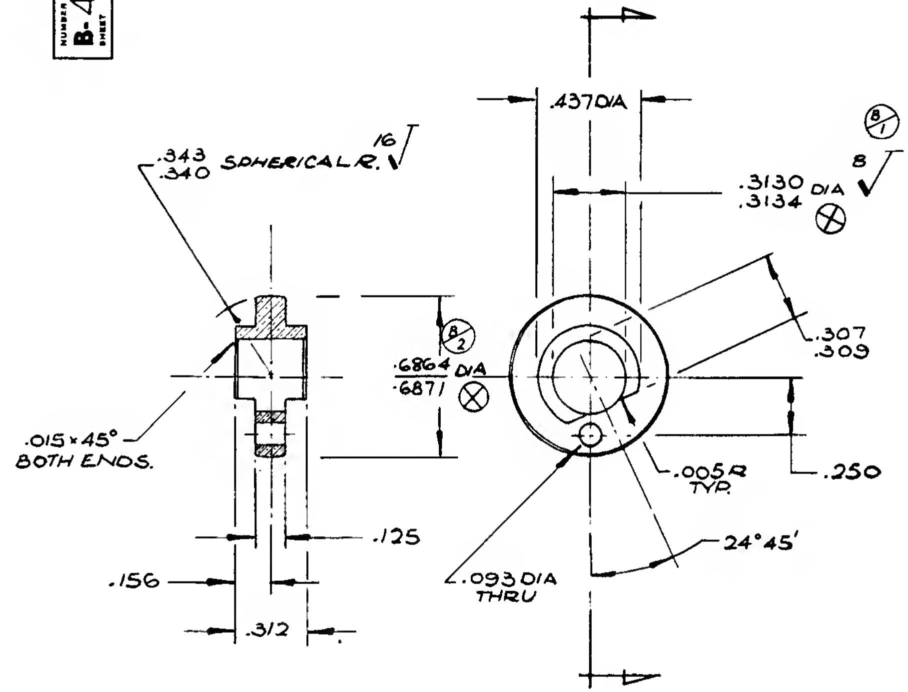
Exhibit 4: Capstan Assembly Drawing.

REVISIONS						
ISSUE	DESCRIPTION	BY	CHKD.	AUTH.	DATE	E.C. NO.
A	RELEASED FOR PROD.	JB			6/22/61	10462
B	① WAS √ ② WAS .6864/.6869. ADDED NOTE 2 & 3. ADDED CATEGORIES FOR SELECTIVE ASSY					10714
C	DWG. NO. WAS 20-0145-01					12810

B-4200145 C

QTY. -4	QTY. -3	QTY. -2	QTY. -10	ITEM NO.	PART NO.	DESCRIPTION

CATEGORY	SIZE	COLOR CODE.	MARKING TAPE.
1	.6864/.6865	RED	71-02 5
2	.6865/.6866	BLACK	71-0027
3	.6866/.6867	ORANGE	71-0217
4	.6867/.6868	GREEN	71-02 8
5	.6868/.6869	YELLOW	71-0219
6	.6869/.6870	BLUE	71-0216
7	.6870/.6871	BROWN	71-0222



3. CAUTION: NO CARBORUNDUM CONTAINING MATERIALS MAY BE USED IN THE MANUFACTURING OF THE PART SUCH AS HONING, SANDING ETC.

2. $\frac{.6864}{.6871}$ DIA. MUST BE LESS THAN .0001 OUT OF ROUND.

1. DIA'S MARKED THUS ⊗ TO BE CONCENTRIC WITHIN .002 T.I.R.

NOTES, UNLESS OTHERWISE SPECIFIED.

DASH NO.	MAT'L. SPEC.	STOCK SIZE	MATERIAL
-10			S.A.E. 660 BEARING BRONZE

ALL DIMENSIONS ARE AFTER PLATING

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
BREAK SHARP CORNERS .005 R. MAX.
TOLERANCE ON DECIMALS ±.005
FRACTIONS ±1/64 ANGLES ½°

SAMPLES MUST BE SUBMITTED AND APPROVED BEFORE PROCEEDING WITH PRODUCTION

SCALE: 2/1

DO NOT SCALE DRAWING

		DATE
DRAWN BY	Black	
CHECKED		7-6-61
PROJ. ENG.		7-6-61
APPROVED		7-6-61

TITLE: BEARING, CAPSTAN SELF ALIGNING

AMPEX AUDIO INC
SUNNYVALE, CALIFORNIA

MODEL	USED ON	NEXT ASS'Y.
PR-10		4030186

NUMBER B-4200145
SHEET 1 OF 1

Exhibit 5: Capstan Shaft Bearing.

INSTRUCTOR'S NOTE

Tape Recorder Capstan Shaft
by G. Kardos

This case can be used to advantage in a machine design course to introduce or provide assignments in the design of sleeve bearings.

Class discussion can be centered around:

1. Definition of boundary layer lubrication and full film lubrication.
2. Why one is desirable and the other is not for the capstan drive.
3. The ZN/P curve and its significance in this case.
4. A method of testing to determine if capstan drive has full film lubrication.
5. A plot of flutter vs. capstan speed.
6. Probable effect of oil grooves used.

There is sufficient information in the case that the student can determine the friction in the bearings using any standard machine design text.